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A MUSCULOSKELETAL MODEL OF THE ELBOW JOINT COMPLEX

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ABSTRACT

This paper describes a musculoskeletal model that represents human elbow flexion-extension and forearm pronation-supination. Musculotendon parameters and the skeletal geometry were determined for the musculoskeletal model in the analysis of ballistic elbow joint complex movements. The key objective was to develop a computational model, guided by optimal control, to investigate the relationship among patterns of muscle excitation, individual muscle forces, and movement kinematics. The model was verified using experimental kinematic, torque, and electromyographic data from volunteer subjects performing both isometric and ballistic elbow joint complex movements. In general, the model predicted kinematic and muscle excitation patterns similar to what was experimentally measured.

INTRODUCTION

Biomechanical investigations of human movement have employed experimental, observational, and, more recently, computational modeling techniques [Anderson and Pandy, 1993]. The latter have provided both qualitative and quantitative insights into muscular control which are not always evident through observation or experimental procedures alone. Our objective was to use computational modeling techniques in investigating Elbow Joint Complex (EJC) movements. We used optimal control theory to solve the problem of muscular force indeterminacy caused by the redundant number of actuators present in the system.

METHODOLOGY

Ballistic movement patterns were executed for the data gathering session. The experimental protocols consisted of various combinations of ballistic elbow flexion, elbow extension, forearm pronation, and forearm supination. To demonstrate how the EJC model executes these movements, one ballistic protocol consisting of elbow flexion with forearm pronation is reported here. For this protocol, the subject was asked to start from a resting position with his humerus (upper arm) horizontal, supported, and strapped, and his forearm at approximately 10° flexion and -50° supination. The subject was asked to perform an elbow flexion with a simultaneous forearm pronation "as quickly as possible" without reaching the extreme positions of either motion.

EMG signals were recorded at 1000 Hertz from eight muscles[1] using five bi-polar surface electrodes and three fine wire intramuscular electrodes (BRA, BRD, and SUP). A digital bandpass filter [Barr and Chan, 1986] was applied to the digitized EMG data with frequency cut-offs at 20-200 Hz. Position data of the forearm were obtained using a triaxial electrogoniometer similar to the one used in previous EJC investigations [Chao et al., 1980] and were also sampled at 1000 Hz. The kinematic raw data were then low-pass filtered using a digital filter at 3 Hz.

MODELING

The model represents elbow flexion/extension (f/e) and forearm pronation/supination (p/s) with eight musculotendon actuators crossing the joint[1]. Ballistic EJC movements were modeled to describe the optimal kinematics, kinetics, musculotendon characteristics, and muscle excitations at the elbow joint. The integrated components for developing computational musculoskeletal models have been established through recent efforts [Pandy et al., 1990]. Existing computer algorithms for modeling the mechanical response of the musculotendon system were used with the predetermined

[1] Biceps Brachii (BIC), Brachialis (BRA), Brachioradialis (BRD), Triceps Brachii (TRI), Supinator (SUP), Pronator Teres (PRT), Anconeus (ANC), and Pronator Quadratus (PRQ).

parameters for the eight actuators. The values for the parameters were based on solutions determined in the model using isometric experimental results [Hutchins E.L., 1993]. Included in this model were the calculations of musculotendon length and velocity, and their corresponding moment arms.

The mechanical redundancy posed by the numerous actuators required that this problem be solved using a numerical optimal control package [Pandy et al., 1992]. This algorithm was used to converge on minimum time sub-optimal solutions of ballistic movements starting from rest and ending at rest.

RESULTS AND DISCUSSION

Results of the computational solution were compared to the experimental kinematic and EMG data. Figure 1 shows both the predicted (modeled) and experimentally measured positions of a ballistic elbow flexion and forearm pronation. The final time difference between the model's solution and the experiment was 12 milliseconds. This comparison indicates an extremely good fit between what the subject performed and what the model concluded was the minimum time solution.

The predicted activations were compared to the processed experimental activations (Figure 2). The BIC, BRA and BRD showed a full initial activation ending between the range of 0.1 - 0.2 seconds into the movement. The model's solution not only indicated the magnitude of the activity for the flexor muscles, but also the amount of time the muscles were active as compared to the EMG. The predicted activation and force in the TRI and ANC showed the classic second burst of activity to brake the elbow's flexion and the TRI compared nicely with the measured EMG. However, the predicted activation of the ANC muscle's did not represent the initial activity shown in the experimental EMG because the ANC muscle is believed to contribute to the stabilization of the EJC (Caldwell, 1987). This stabilization was not accounted for in the EJC model. The magnitude of the processed SUP EMG signal was unusually high because it was normalized to its respective maximum.

In general, the model predicted muscle excitation patterns similar to the processed EMGs. The variations between the computed and experimental muscle activations are attributed, in part, to the processing of the raw EMG data and the manner in which neural to muscle activation is modeled. Overall, the presence of the tri-phasic activation pattern in the model's solution, especially for f/e, and the reasonably good comparison with experimental measurements (i.e. kinematics and muscle activity) validates the model and thus gives credence to the time-varying muscle force predictions.

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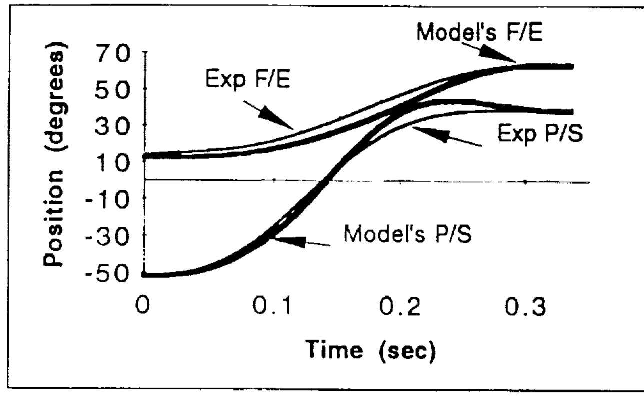

Figure 1. Experimental (light) and model predicted (bold) position trajectories are shown for elbow f/e and p/s. Zero degrees was full elbow extension and neutral forearm position. Negative angles were for supinated forearm positions.

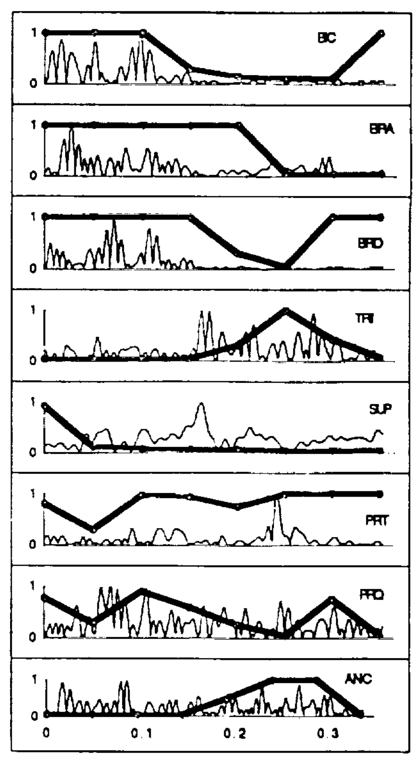

Figure 2. Musculotendon activation is shown for bandpassed rectified normalized EMG (light) and nominal muscle activation used by the model (bold).